

Evidence for Quark Gluon Plasma from Hadron Production in High Energy Nuclear Collisions *

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The experimental results on the pion, strangeness and J/ψ production in high energy nuclear collisions are discussed. The anomalous energy dependence of pion and strangeness production is consistent with the hypothesis that a transition to a deconfined phase takes place between the top AGS (≈ 15 A·GeV) and the SPS (≈ 200 A·GeV) energies. The J/ψ production systematics at the SPS can be understood assuming that the J/ψ mesons are created at hadronization according to the available hadronic phase space. This new interpretation of the J/ψ data allows one to establish a coherent picture of high energy nuclear collisions based on the statistical approaches of the collision early stage and hadronization. Surprisingly, the statistical model of strong interactions is successful even in the region reserved up to now for pQCD based models.

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1. Introduction

The basic motivation for a broad experimental program of nucleus–nucleus (A+A) collisions at high energies is the search for the Quark Gluon Plasma (QGP) [1]. An impressive set of experimental data has been collected during the last decades and many unexpected phenomena have been discovered [2]. The results indicate surprising scaling behaviours which find a natural interpretation within statistical models of the early stage of the collision [3] as well as the hadronization [4, 5]. Within this framework one concludes that the results are consistent with the hypothesis of a QGP creation in A+A collisions at the SPS [3]. The collision energy region in which the transition to QGP takes place is located between the top AGS (≈ 15 A·GeV) and the SPS (≈ 200 A·GeV) energies.

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This interpretation, however, is still under vivid discussion, because the statistical models are not commonly recognized as valid tools to investigate high energy nuclear collisions. Indeed, their basic assumptions cannot be derived from QCD.

On the other hand it is difficult to use QCD for the interpretation of the experimental results. Problems arise because almost all effects expected in the case of the transition to QGP are in the domain of the so-called soft processes for which experimentally testable predictions of QCD are not available. Attempts to build phenomenological QCD inspired models are not very successful [6] either. Conclusive interpretation of the data within these models seems to be impossible as one cannot estimate the uncertainties due to the used approximations.

Thus, the question whether QGP is created in A+A collisions at high energies unavoidably leads to the more fundamental question about our understanding of strong interactions.

The aim of this contribution is a brief discussion within the framework of the statistical models of the data on the pion, strangeness and J/ψ production in nuclear collisions.

2. Pion Production

The majority of particles produced during high energy interactions are pions. Thus, pions carry basic information on entropy created in the collision and consequently their yield should be sensitive to the effective number of degrees of freedom at the early stage. The energy dependence of mean pion multiplicity in nucleon–nucleon (N+N) interactions is plotted in Fig. 1 [7]. The pion yield appears to be proportional the energy measure introduced by Fermi [8]:

$$F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}, \quad (1)$$

where $\sqrt{s_{NN}}$ is the c.m. energy for a nucleon–nucleon pair and m_N is the nucleon mass. This dependence was predicted by Fermi [8] and Landau [9] almost 50 years ago. It follows directly from the assumption that the most probable (maximum entropy) state is created in the early stage of the collision. The energy dependence of the pion yield in central A+A collisions is different from that observed for N+N interactions. The comparison is presented in Fig. 2 [7] where the difference between the average number of pions per wounded nucleon (participant) in A+A and N+N interactions [10] is shown as a function of the collision energy. At low energies (the AGS and below) the pion production in A+A collisions is significantly suppressed in comparison to N+N interactions. This suppression can be understood as due to entropy transfer to the baryonic sector [11] during the expansion

of the matter [12]. The pion enhancement effect is observed in central A+A collisions at the SPS [13]. The change from the pion suppression to pion enhancement pattern can be attributed to the transition to the QGP occurring between the AGS and the SPS energies. In fact, the statistical model of the early stage, which assumes this transition, correctly reproduces the data [3], see solid line in Fig. 2. In the model the pion enhancement is due to the increased entropy content of the deconfined matter.

3. Strangeness Production

The energy dependence of the strangeness to pion ratio in A+A and N+N interactions is compared in Fig. 3 [7] where the ratio

$$E_S \equiv (\langle \Lambda \rangle + \langle K + \bar{K} \rangle) / \langle \pi \rangle \quad (2)$$

is plotted as a function of F . Between the AGS ($F \approx 2$) and the SPS ($F \approx 4$) energies the ratio for N+N interactions increases by a factor of about 2. Very different behaviour is observed for central A+A collisions, where no significant energy dependence is observed. The latter behaviour can be interpreted as due to the transition to the QGP taking place between the AGS and the SPS energies. The statistical model of the early stage suggests that the ratio should reach a maximum at the beginning of the transition region [3], see solid line in Fig. 3. Thus, a non-monotonic energy behaviour of the strangeness to pion ratio is predicted; the transition is signal by the suppression of the strangeness to pion ratio.

We note that in the picture of the non-equilibrium strangeness production a very different conclusion is reached [14], namely the strangeness enhancement is expected to be a signal of the transition.

4. J/ψ Production

Since a long time the production of J/ψ mesons has been considered as a sensitive probe of the state of matter in the early stage [15, 16]. This reasoning is based on the assumption that the J/ψ meson (or its pre-state) is produced at the very beginning of the collision process due to the coalescence of the $c\bar{c}$ pairs produced in the hard QCD process [17]. This orthodox picture suggests also that the Drell-Yan pairs should be used as a proper reference for the J/ψ study. Within this framework a complicated pattern of J/ψ suppression was established experimentally by the NA38 and NA50 Collaborations [18, 19]. The analysis of this pattern suggests that the deconfined matter is created only in central Pb+Pb collisions where an anomalous suppression was observed.

This conclusion as well as the theoretical framework leading to it are very different from the pion and strangeness cases discussed in the previous sections. Thus, the picture of the A+A collision process seems to be inconsistent.

It has been, however, recently found [3, 20] that the J/ψ multiplicity increases proportionally to the pion multiplicity in collisions from p+p to central Pb+Pb at the SPS. The ratio of the J/ψ multiplicity to the multiplicity of negatively charged hadrons (mostly π^- mesons) is plotted in Fig. 4 [21]. The approximate independence of the ratio of must be accidental when considered in the orthodox picture of J/ψ production.

This scaling behaviour finds, however, a natural explanation in the model of the statistical production of J/ψ mesons at the hadronization [21]. We recall here that the statistical models of hadron production (hadronization) are successfully used to describe the data from the central Pb+Pb collisions as well as from the interactions of elementary particles (p+p, e^+e^-). The temperature parameter which defines the available phase-space is found to be energy and system size independent (for sufficiently high energies) [4], it ranges between 160–190 MeV. In order to reproduce the measured J/ψ yield the temperature parameter $T \approx 176$ MeV is needed [21]. It is in good agreement with the values obtained in the analysis of hadron yield systematics. The statistical approach to the J/ψ creation allows for a coherent interpretation of the results on pion, strangeness and J/ψ production in nuclear collisions. It changes however in a significant way the role of the J/ψ meson. As being produced directly at the hadronization it is not sensitive to the form of prehadronic matter. But due to its large mass and small cross section for hadronic interactions it can serve as a sensitive probe of the hadronization process.

5. Event-by-Event Fluctuations

The question whether statistical models can serve as a valid description of the A+A collision process is crucial in the interpretation of the experimental results. The discussion presented above was based on the analysis of the inclusive data on hadron production, i.e. the results obtained by averaging over a class of selected events (e.g. central collisions). A key test of the validity of the statistical approach can be done by the study of event-by-event fluctuations. Large acceptance, high statistics and high quality data obtained by the NA49 experiment [22] allow one to perform such an analysis of many observables.

The event-by-event fluctuation of the mean transverse momentum and the kaon to pion ratio for central Pb+Pb collisions at 158 A·GeV are shown in Fig. 5 [24, 25]. The data are compared with the fluctuations simulated

for the case of independent particle production where the multiplicity distribution of generated events is equal to the measured one (the 'mixed event' procedure). This procedure gives fluctuations as expected in the statistical model within the grand canonical ensemble [26] when the small effects due to quantum statistics, Coulomb interaction and resonance decays are neglected. The measured fluctuations indeed appear to be close to those expected in the statistical models, see Fig. 5.

Systematic, quantitative study of event-by-event fluctuations is done using the Φ measure of fluctuations [27]. It allows to remove the influence of 'unwanted' fluctuations of the volume (number of wounded nucleons) of colliding nuclei. The values of Φ_{P_T} (the transverse momentum fluctuation measure) obtained for all inelastic p+p interactions and central Pb+Pb collisions at 158 A·GeV are shown in Fig. 6 as a function of the number of wounded nucleons [24]. The influence of short range correlations due to quantum statistics and Coulomb interaction is removed from the result. The value of Φ_{P_T} for central Pb+Pb collisions is consistent with zero, the value of Φ_{P_T} calculated in the statistical model in grand canonical ensemble for classical particles [26]. The non-zero, positive value of Φ_{P_T} for p+p interactions can be attributed to the influence of the energy-momentum conservation, its role appears to be significant for the small systems [28]. Calculations in the micro-canonical ensemble are needed here. In the approaches where the A+A collisions are modelled as an independent superposition of N+N interactions the value of Φ in A+A collisions is equal to the corresponding value for the elementary process [27].

We conclude that the fluctuations measured in central Pb+Pb collisions at the SPS confirm the validity of the statistical approach used to interpret the inclusive results.

6. Summary

Statistical models of the early stage and the hadronization in high energy nuclear collisions allow one a coherent interpretation of the wide spectrum of the experimental data. Within this interpretation:

- the energy dependence of pion and strangeness yields serves as an evidence for Quark Gluon Plasma creation in A+A collisions at the SPS;
- the transition to the deconfined state takes place between the top AGS and the SPS energies and should be reflected by a non-monotonic dependence of the strangeness to pion ratio in the intermediate energy region;

- the systematics of the J/ψ production can be understood assuming the statistical creation of the J/ψ mesons at the hadronization; within this interpretation the yield of J/ψ mesons is independent of the properties of the early stage matter, but it is sensitive to the hadronization process.

Analysis of the event-by-event fluctuations in high energy collisions yields a crucial, independent test of the validity of the statistical approach. The observed fluctuations are consistent with those expected in the statistical models.

Finally, we repeat once more that the interpretation discussed above is based on the analysis within statistical models. The validity of this approach is however controversial. Thus, the question whether QGP is created in A+A collisions at the SPS leads us to questions about our understanding of strong interactions. It is clear that the increasing flow of new experimental data on nuclear (p+p, p+A and A+A) collisions should soon result in a substantial progress in this domain.

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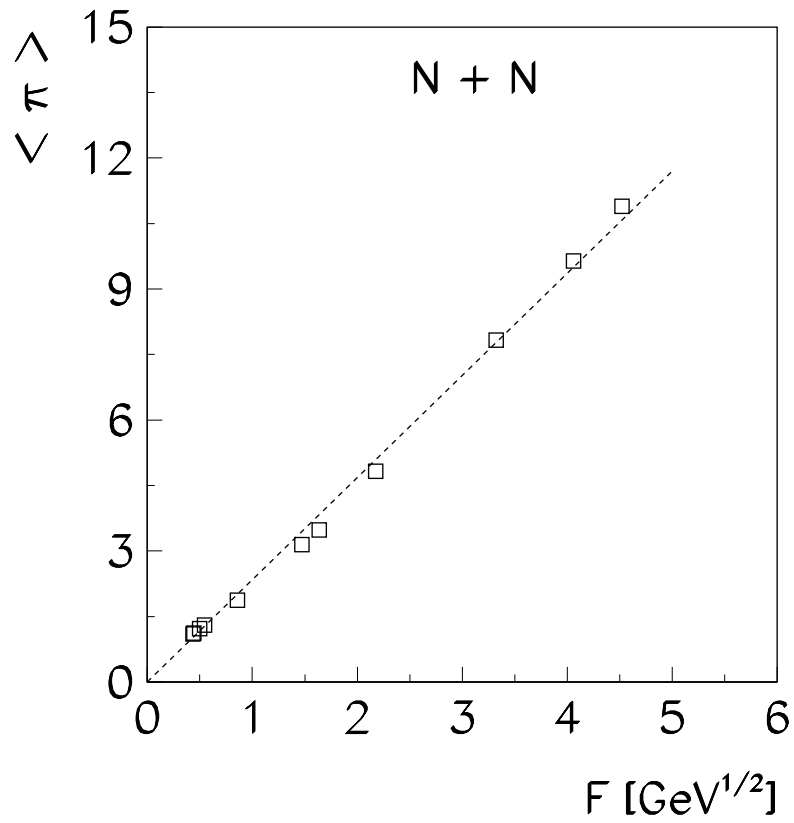


Fig. 1. The dependence of the mean pion multiplicity for all inealstic nucleon–nucleon interactions on the collision energy measured by the Fermi energy variable, $F = (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}$. The dashed line is plotted to guide the eye.

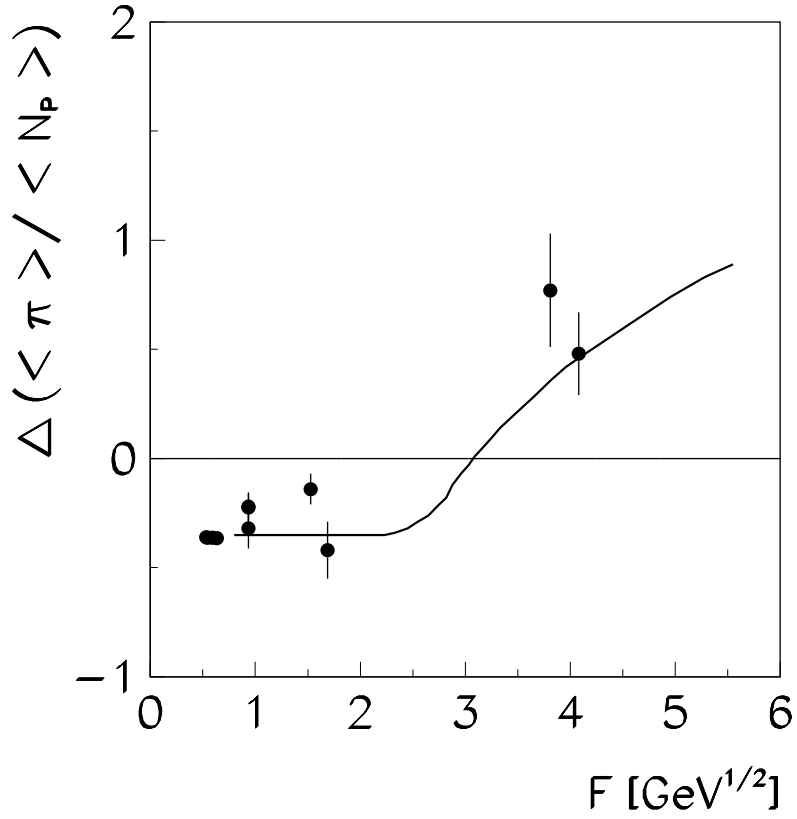


Fig. 2. The dependence of the difference between pion/baryon ratios for central A+A collisions and nucleon–nucleon interaction at the same energy per nucleon on the collision energy [7] measured by the Fermi energy variable, $F = (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}$. The solid line shows predictions of the statistical model of the early stage assuming transition to the QGP between the top AGS ($F \approx 2$) and SPS ($F \approx 4$).

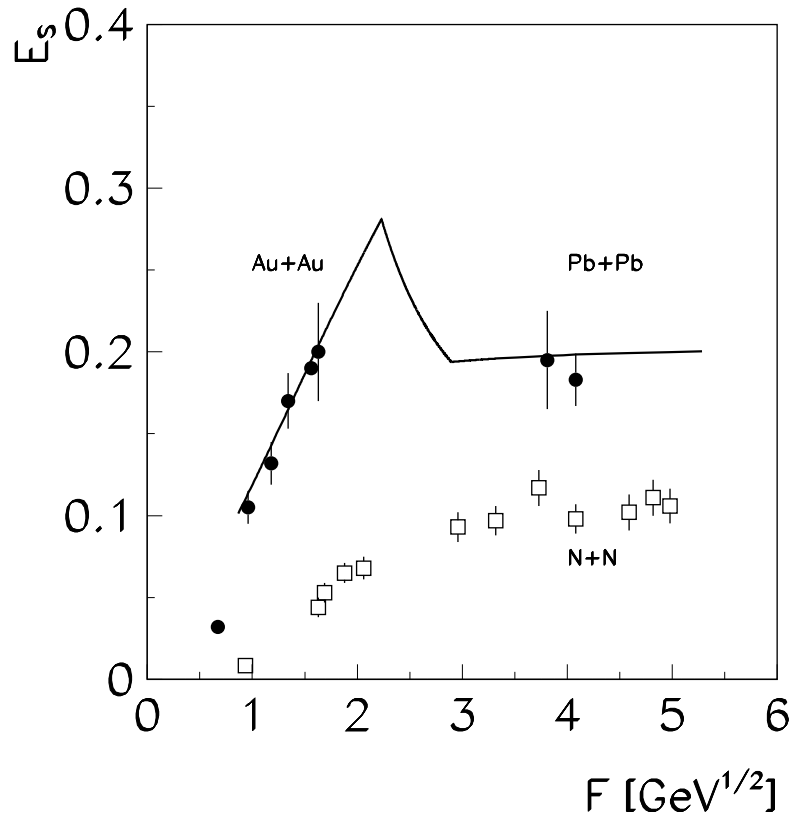


Fig. 3. The dependence of the strangeness/pion ratio, $E_S = (\langle \Lambda \rangle + \langle K + \bar{K} \rangle) / \langle \pi \rangle$, for central A+A collisions (closed circles) and nucleon-nucleon interactions (open squares) as a function of collision energy [7] measured by the Fermi energy variable, F . The solid line shows predictions of the statistical model of the early stage assuming transition to the QGP between the top AGS ($F \approx 2$) and SPS ($F \approx 4$).

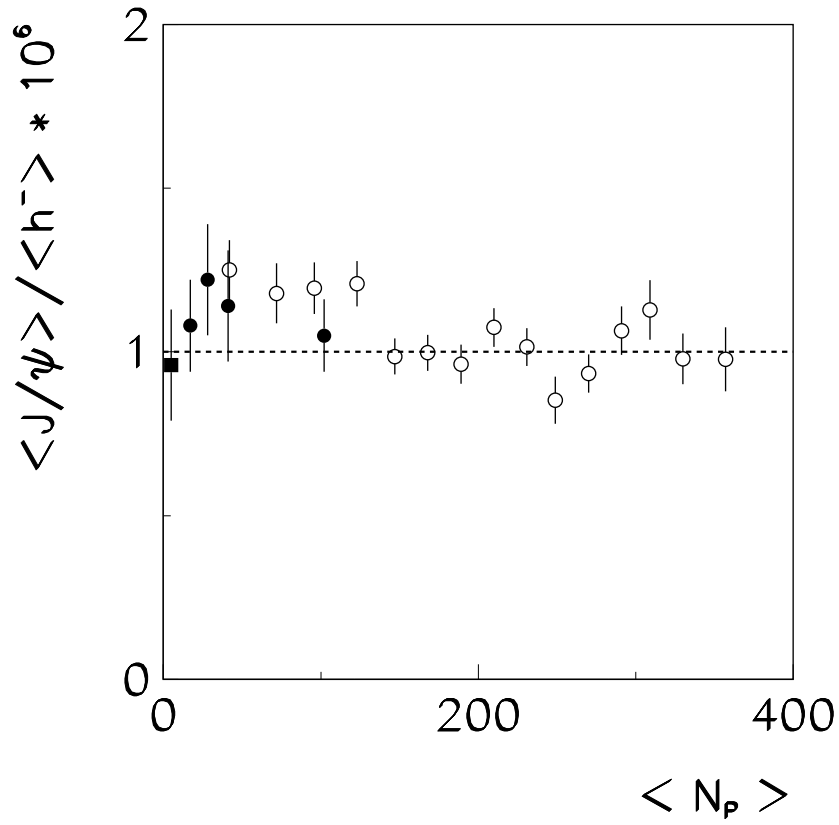


Fig. 4. The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A·GeV plotted as a function of the mean number of participant nucleons. For clarity the N+N point is shifted from $\langle N_P \rangle = 2$ to $\langle N_P \rangle = 5$. The dashed line indicates the mean value of the ratio.

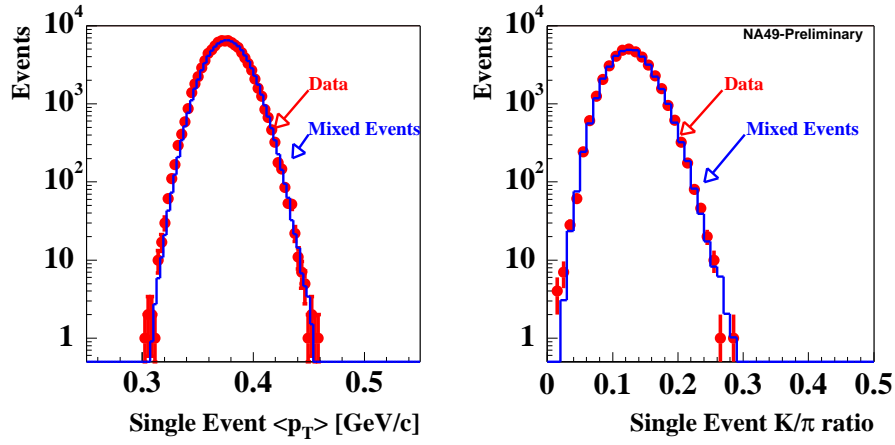


Fig. 5. The event-by-event fluctuations of the mean transverse momentum and the kaon to pion ratio for central Pb+Pb collisions at 158 A·GeV. The solid lines indicate fluctuations calculated assuming independent particle emission (the 'mixed event' procedure).

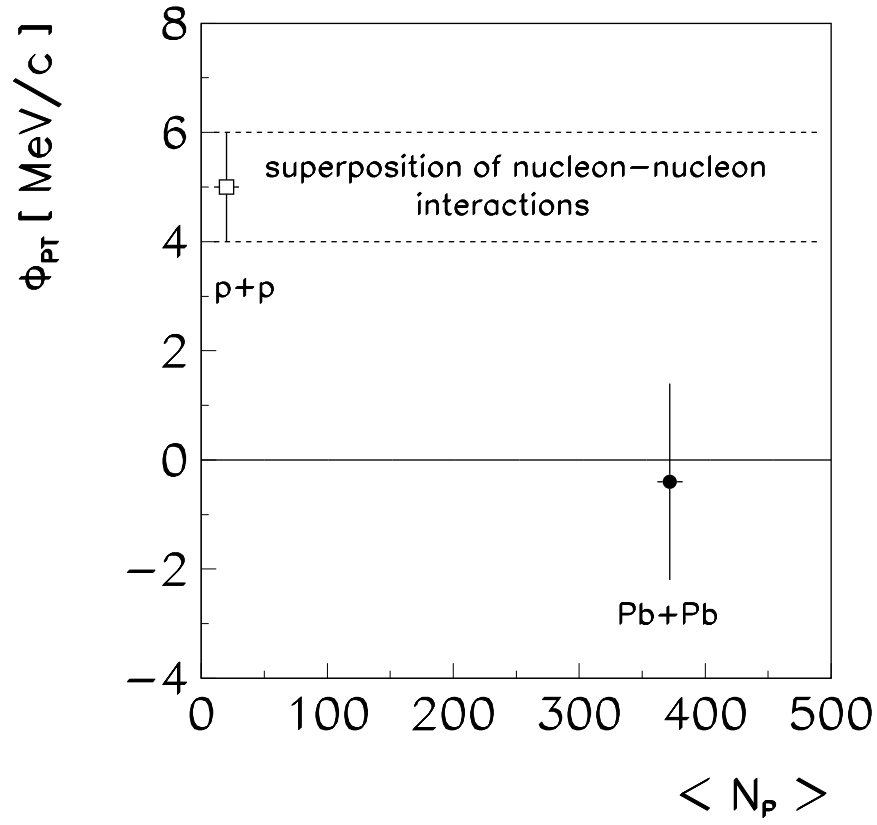


Fig. 6. The Φ_{pT} fluctuation measure dependence on the number of wounded nucleons. The two data points show results of the NA49 Collaboration for all inelastic p+p interactions and central Pb+Pb collisions at 158 A·GeV.